Electrical Property of Precipitating Clouds -Raindrop Charge-size Measurements-

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Abstract

Observational studies of precipitation electricity have been made in order to clarify the mechanical relation between cloud electrification and the growth of hydrometeors. In this paper, an instrument for the simultaneous measurement of charge and size of raindrops is described, and the results of the raindrop charge-size and the electric field measurements for three typical rainfalls are also described.

The electric field disturbances accompanying the passage of precipitating convective clouds usually implied that the clouds were electrified in an ordinary polarity of dipoles. When a cloud was isolated and non-thundery, the field often carried out a well defined W-shaped time change. Mirror-image relation between the polarity of raindrop charge and that of electric field seldom held.

The field disturbances associated with thunderclouds implied the existence of appreciable point discharge at the ground. Large raindrops showed the mirror-image relation, while smaller ones did not. In both cases of thundery and non-thundery, some of the raindrops carried excessive charges that couldn't be explained by the processes of polarization charging or selective ion capture.

In the cases of continuous rain, weak electric field is not likely to affect selective ion capture. The positive charge on a drop and the negative one are nearly the same in magnitude and fluctuate almost in phase. The larger the drop diameter is, the earlier the fluctuation in the drop charge rises, which implies that the charging processes mainly occur aloft.

The relation of raindrop charge and the rainfall intensity implied the important role of the interaction of hydrometeors on cloud electrification.

1. Introduction

Sufficient models have hardly been established concerning the mechanical relations between cloud electrification and the growth of hydrometeors. Precipitation particles charged in a cloud, for example, by the inductive polarization mechanism (Ziv et al[1], Scott et al[2]), experience various re-charging processes beneath the cloud; melting (Kikuchi[3),4)]), breakup, selective ion capture, evaporation (Takahashi[5]), etc. The raindrop charges, despite their importance, have not been frequently measured (Ratcliffe et al[6], Selvam et al,[7] Wishart,[8]Kikuchi et al[9]), partly because of the disadvantages that the raindrops lose much information about their history of growth in the melting layer and that these charging mechanisms cannot easily be separated. Nevertheless the simultaneous observations of raindrop charge-size and electric field may present rare information concerning their history of growth (Smith,[10] Takahashi et al,[11] Bradley et al,[12] Takahashi,[13] Fujiyoshi et al[14]). Many previous works were case studies and demanded more intense and successive observations. In this study, the device for the raindrop charge-size measurement was developed and applied for making observations during 1977–1981 at Uji, Kyoto.

Precipitation is classified into three types; non-thundery convective shower, thunderstorm and continuous rain. Relatively long duration and steadiness of weak rain distinguish continuous rain from a convective shower. The continuous rains are often accompanied by the periodical wave pattern of surface electric field, especially when a rainfall is relatively intense. Such a wave pattern occurs more frequently in convective showers. Therefore, electric field disturbance alone cannot determine whether the rain is of convective origin or not. Unpredictable outbursts of field disturbance, however, can distinguish the convective shower from continuous rain. Thunderstorms are specified by lightning discharges which impress "kicks" upon the electric field as well as by acoustic or visual inspection. Typical examples of each type are discussed in the following chapter.

2. Instruments

An optical raindrop spectrometer (Gocho[15]) was specially arranged for the simultaneous measurement of raindrop charge. Its mechanical array is similar to that of Ratcliffe et al[8] or Bradley et al.[16] The sensor of the charge detector consists of coaxial brass cylinders which have an electro-static capacitance C of an order of 10 pF, given in the following equation,

$$C = 2\pi\varepsilon_0 h / \ln(r_2/r_1), \tag{1}$$

where r_1 and r_2 are the radii of the inner cylinder and the outer, respectively, h is the length of the cylinders and ε_0 is the permittivity of vacuum. When a raindrop having a charge q passes through the inside of the inner cylinder, some portion of charge q' is induced on it, which causes a potential difference V between the cylinders. Thus

$$q' = CV. \tag{2}$$

This spectrometer has a sampling area 4 cm square and the charge detector is housed below it. It is desirable that these cylinders be large enough to cover the whole area, especially when account is taken of the wind effect. However, this inevitably brings about the disadvantages that two or more raindrops simultaneously pass the sensor or that rather a flimsy construction may be a cause of undesirable noise. Thus the inner cylinder must have the diameter of about 10 cm.

The ratio,

$$f = q'/q, \tag{3}$$

which is smaller than unity, is a sensitive function of the position of the charge inside the sensor. Following Owolabi et al,[17] the distribution of f is estimated for such an example as is adopted in this study, and is given in **Fig. 1**. Along the traces of raindrops falling vertically under the condition of weak wind, f has a maximum f_0 halfway in the cylinder, and the corresponding value of V can be detected as a pulse height of the charge signal.

This figure also indicates that the values f_0 vary in some degree with the position of the path; if the raindrop passes the very center of the sensor, $f_0 = 0.66$, while $f_0 = 0.80$ at the edge of the sampling area. This inhomogeneity of the sensitivity will greatly diminish either with increasing size of the sensor, or with its increasing length. Our instrument has the inhomogeneity of $\pm 10\%$ but is still larger in an appreciable wind, which is given in **Fig. 2** together with the calibration by dripping test charges.

Fig. 3 shows the diagram of the instruments. Beside the theoretical estimation of the value C described above, it can also be directly measured. When the test charges hit the inner cylinder, exponential decays in V are recorded. Measuring the time constant of decay τ, which is a product of the capacitance C of the sensor and its shunt resistance R, we obtain $C = 17$ pF, a little different from the value of 15 pF derived by eq. (1).

Finally we get

$$q = CV/f_0 . \tag{4}$$

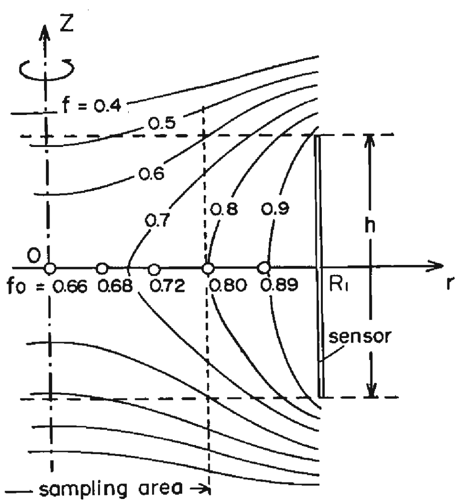

Fig. 1 An example for the distribution of sensitivity f inside the induction cylinder (ratio $h/R_1 = 1.0$). Boundary condition is that the electric potential $\phi = 0$ at $z = \pm R_1$. The edge of the sampling area in the case of $R_1 = 5.0$ cm is shown. It is also indicated that the maximum sensitivity f_0 is 0.66 if the raindrop passes the center of the cylinder and that f_0 is 0.80 if it passes the edge of the sampling area.

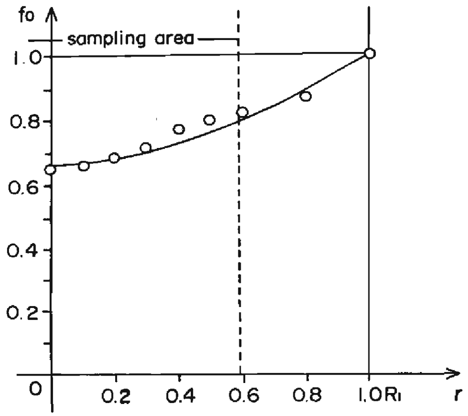

Fig. 2 A calibration of maximum sensitivity f_0 for various paths of raindrops inside the cylinder. Theoretical estimation is given in the solid line and the direct measurement in dots. These are normalized at the wall of the cylinder where f_0 is assumed to be unity.

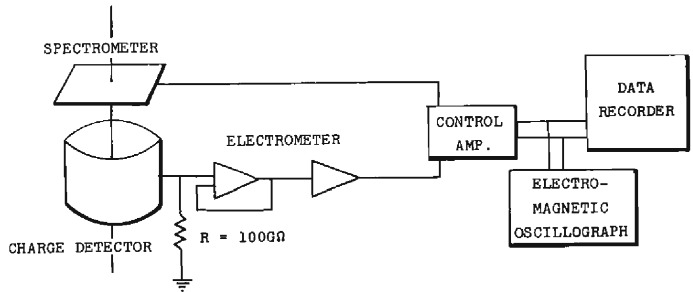

Fig. 3 A diagram of the instrument.

Artificially charged water drops dripping from the injector have charges given in

$$q = 2\pi\varepsilon_0 D V_N, \tag{5}$$

where D is the diameter of a drop and V_N is the potential of the injection needle. Our test charge of 0.123 pC when $D=2.21$ mm and $V_N=1.0$ V caused the output of 4.0 mV. Eq. (4) shows that $q=0.103$ pC if $f_0=0.66$ and $C=17$ pF. The discrepancy seems to be in good agreement with the shielding effect of the injector pointed out by Orikasa.[18] It is noteworthy, however, that the shunt resistor permits an error of 30% and that the estimation of the length of the cylinders leaves a little uncertainty. Internal errors of tens of percent are inevitable. Nevertheless it is adequate for the simultaneous measurement of raindrop charge-size.

The smallest raindrops of 0.06 mm in diameter, if any, would be detectable, and the measurable charges range between 1 fC and 100 pC. Both signals of the raindrop charge and size are directly recorded on an electro-magnetic oscillograph and these pulse heights are manually measured. Continuous observation of the surface electric field has been made by the field mill. All observations were made on the ground surface at Disaster Prevention Research Institute, Uji, Kyoto. Our polarity convention is that a positive test charge is forced to make a downward motion in a positive electric field.

3. Results

3.1 Convective shower

When a precipitating convective cloud is isolated and non-thundery, the time change of the surface electric field often carries out a well defined W-shaped disturbance during the passage of the cloud accompanied by a temporary shower burst. **Fig. 4** shows such a time change of the electric field E, the rainfall intensity R and the rainfall current density i on 13 Sep. 1979.

The negative trend of the field disturbance which had a duration of about an hour with the maximum intensity of -3000 V/m was overlapped by a rapid positive excursion to $+2000$ V/m around 16:05. The rainfall began at 15:59 and lasted till 16:26, with the maximum intensity of 6 mm/h. The hourly rainfall rate is converted from the rainfall mass flux per minute, which is measured by the spectrometer. The total rainfall was 1.2 mm. The negative rainfall current was predominant throughout the rain. The mirror-image relation between the polarity of the raindrop charge and that of the electric field was not found. The raindrop charge-size distribution during this rain is represented in **Fig. 5** (right) together with a similar case on 17 Feb. 1979 (left). The

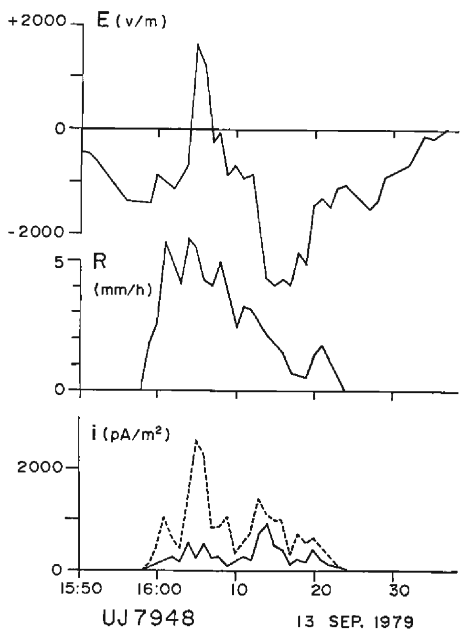

Fig. 4 The time change of the surface electric field E, the rainfall intensity R and the rainfall current density i during a non-thundery convective shower. The positive current density is represented in a solid line and the negative one in a broken one.

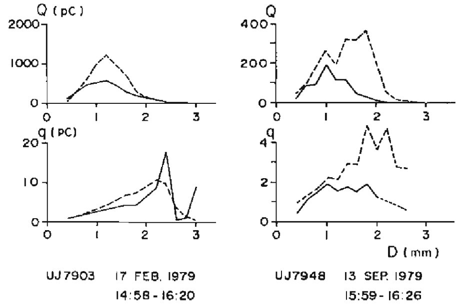

Fig. 5 Raindrop charge-size relations during non-thundery convective shower. Q is the total charge carried onto the ground during the whole period of rainfall and q is the average charge on a raindrop. Solid and broken curves indicate the positive and negative contribution, respectively. Q and q are given in every 0.2 mm in diameter D of raindrops.

value of raindrop charge flux Q in the figure can directly be converted into the rainfall current density; the sampling area of our spectrometer is 16.0 cm^2. Negative charges were predominant in both cases. Relatively large raindrops mainly carried negative charges to the ground, while the smaller ones were charged in both polarities, thus the former contributed most to the negative predominance of the rainfall current density as well as the rainfall mass flux. Rough inspection of the average charge on a raindrop implies that the charges are proportional to the raindrop diameters.

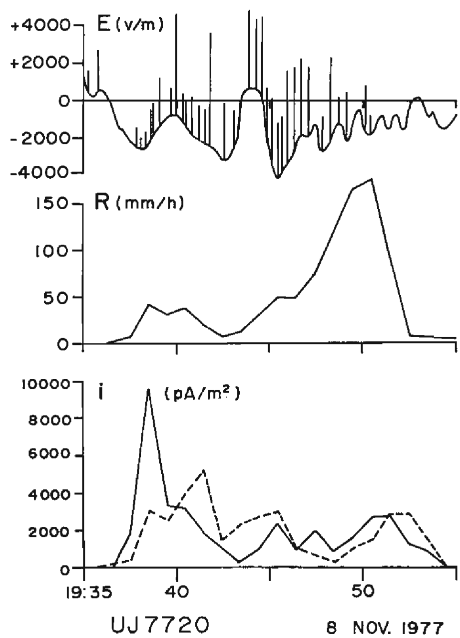

Fig. 6 The same as in Fig. 4, except during a thunderstorm. Overlapping positive-ward spikes on the trend of the electric field indicate the lightning discharges.

3.2 Thunderstorms

A severe cold front accompanied by thunderstorm passed over our observation site on 8 Nov. 1977. The time changes of the electric field, the rainfall intensity and the rainfall current are represented in **Fig. 6**.

During the storm, the field carried out an intense negative excursion overlapped by the abrupt discontinuities due to the lightning discharges, the polarity of which implies the removal of negative charge from the relatively lower region of the cloud. Thus it is supposed that the positive charges were predominantly concentrated in the upper region in the cloud and the negative ones in the lower. Though we have no such evidence that would identify the positive pocket charges at the cloud base by the transitory positive excursion of the field around 19:44, the active center of the thundercloud was supposed

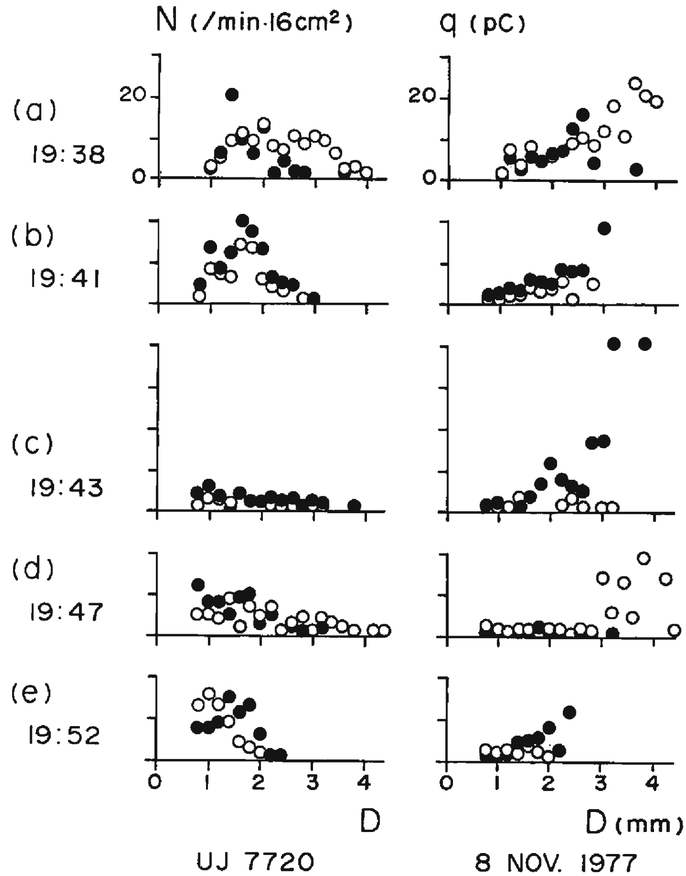

Fig. 7 Raindrop charge-size relations during a thunderstorm described in Fig. 6. N is the number flux of charged raindrops during 1 min., and q is the average charge on a raindrop. These are given in every 0.2 mm in diameter D of raindrops. Open and closed circles indicate the positive and the negative charges, respectively.

to be above the observation site then; around that time the field was disturbed by frequent lightning. A burst of rain, 5 minutes later, struck the ground at the maximum intensity of 178 mm/h (3.0 mm/min) after the passage of thundercloud. The polarity of the rainfall current and that of the electric field roughly showed a mirror-image relation except when the rainfall was diminishing.

Fig. 7 gives some of the typical raindrop charge-size relations. At 19:38 (a) when the positive current was at its maximum, large raindrops showed an intense positive electrification both in number and in average charge, while smaller ones were charged in both polarities. The distribution at 19:47 (d) when the field was negative also represents the same pattern. At 19:43 (c) the field reversed its polarity slightly into positive, and the distribution was quite similar to those given in (a) or (d) except the whole reversal in the polarity. The distributions (b) and (e) are other examples that did not show a mirror-image relation. Any raindrop including non-charged ones, larger than 3 mm in diameter was not found.

3.3 Continuous rain

Weak rain of the intensity around a few mm/h lasts for several hours. This is often brought about by the stratiform clouds in the northern sector of a warm front. The electric field which occasionally alternates its polarity seldom exceeds 2000 V/m and is usually below 1000 V/m. **Fig. 8** shows an example of rainfall on 29 Mar. 1979. The rainfall intensity is steady except during the period 19:55–20:00. In spite of the steadiness of rainfall the current density varies dramatically. Around 19:39 and 20:14, the rainfall current is much larger than that in the surrounding periods in both polarities, though the rainfall is only a little more intense. This implies that the increase of the average charge on a raindrop caused the intensification of the current density

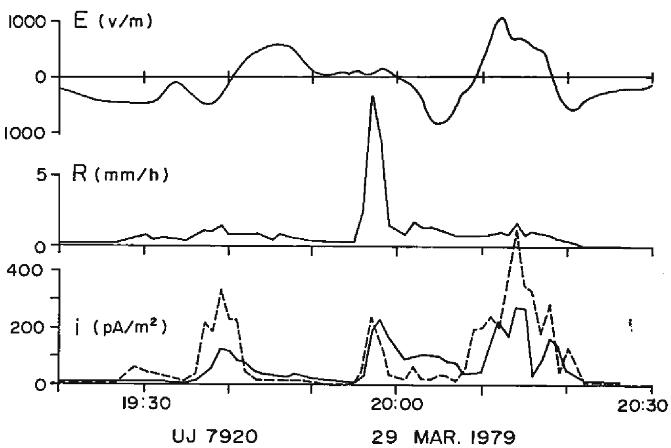

Fig. 8 The same as in Fig. 4, except during a continuous rain.

around these periods. On the contrary, the peak in the current density at 19: 57 is obviously caused by the sudden burst of strong rain, that is to say, the increase in the number flux of raindrops. The average charge in this period was rather less than that in the surrounding periods. This is clear in **Fig. 9**, which represents the time change of the average charge on a raindrop of various diameter. We cannot detect any intensification in q around 19: 57.

Fig. 9 also represents another feature for the time-lag in the occurence of the peak in q at each diameter. The smaller the raindrop diameter is, the more the peak occurence in q delays, which implies that the electrification of

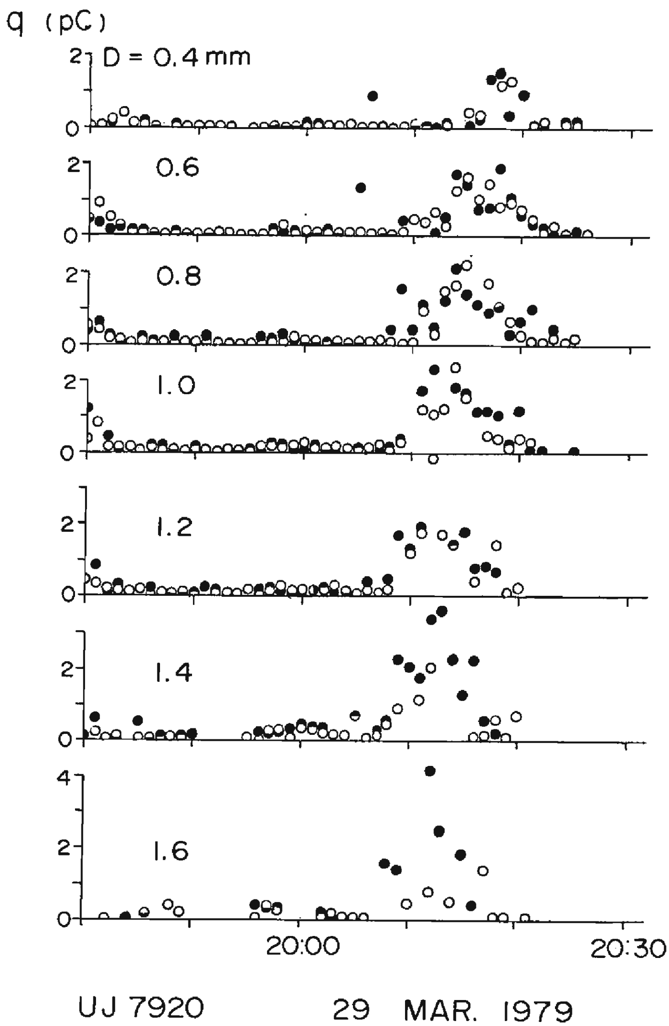

Fig. 9 Time change of the average charge on a raindrop during the rain in Fig. 8. These are given for various raindrop diameter. Open and closed circles indicate the positive and the negative charges, respectively.

raindrops in both polarities is prevalent at some altitude of a few kilometers. As is often the case with the continuous rain, the values of q are similar for both of the polarities; the occasional polarity alternation in the rainfall current is mainly caused by the number flux in each polarity.

4. Discussions

Some of the abrupt discontinuities in the electric field due to the lightning discharges (**Fig. 6**), crossing the zero line, intruded into the positive side, and those which occured during the positive field excursion even enhanced the field. These imply the existence of appreciable positive space charges due to the point discharge near the ground, and their appropriate portion must have been captured by falling raindrops. Though some of the large raindrops might have attained positive charges in the mechanism of selective ion capture (Abbas et al[19]) under the negative field during the periods when the mirror-image relation held, the negative charges observed at the same time cannot be explained. Moreover, the mirror-image relation at 19:43 (**Fig. 7(c)**) does not seem to be well founded.

At the base of a thundercloud which is charged in an ordinary polarity of dipole, i.e. predominant positive charges are distributed at the upper portion in the cloud and the negative ones at the lower, the observed precipitation charges are predominantly negative (Rust et al,[20] Gaskell et al[21]), which seems to be coinsident in the polarity with the numerical prediction of the polarization charging mechnisms in the cloud (Scott et al,[2] Levin[22]).

We usually observed charges of both polarities simultaneously being carried on raindrops. Therefore another charging process which produces the positive raindrops beneath the cloud must be taken into account. Each process of selective ion capture, breakup, evaporation (Takahashi[5]) and melting of ice (Magono et al,[23,24] Kikuchi[3][4]) assists this positive re-charging process. It is, however, quite difficult to separate them from each other.

In the cases of continuous rain, the weak electric field observed in this study is not likely to affect the selective ion capture beneath the cloud. The average positive charge on a raindrop is nearly the same in magnitude as a negative one and both fluctuate in phase. The larger the raindrop is, the earlier the fluctuation in q rises at the ground, which implies that the main charging process exists at a certain altitude, at least 1 km above the ground. This coinsides with the result of the recent observational study for the middle-level precipitating clouds by Fujiyoshi et al,[14] which revealed that the electric field frequently changed its polarity with a large amplitude where the generating cells in the stratiform cloud were in close vicinity to each other: there hydrometeors of the different types from the cells of the different life stages would coexist growing either in masses or in charges.

We now define the charging efficiency k of a raindrop:

$$q = kD^2, \tag{6}$$

though the charge-size relations observed here usually implied that the raindrop charge q was somewhat proportional to the diameter D, not to the square of D. Eq. (6), which has some physical rationality that the charges are scattered on the surface of a conductor, is also derivable from the theory of polarization charging (Illingworth et al[25]):

$$q = -5.5 \times 10^{-5} E_H D^2, \tag{7}$$

and from the theory of selective ion capture (Wormell,[26] Smith[10]):

$$q = -8.3 \times 10^{-5} E_L D^2. \tag{8}$$

Most of the convective clouds studied here had the ordinary polarity of dipoles. Then these equations (6), (7) and (8) allow us to estimate the maximum positive electric field E_H in the cloud and the negative one E_L beneath the cloud.

Such an assessment is given in **Fig. 10 (a)** and **(b)** for all the case studies during 1977–1981, where E_0 is the maximum intensity of the negative electric field at the ground during each rainfall. The values of E_H and E_L are one or two orders greater than those of E_0 for continuous rain, and two or three orders greater for thunderstorm or convective shower. In the cases of continuous rain, E_H and E_L as well as E_0 are small, while the convective clouds show intense electrification: it is striking that even in the non-thundery convective shower the raindrops experience as intense an electrification as in the thunderstorm. Some of E_H, even for the non-thundery shower, exceed the lightning breakdown field of 350 kV/m (Griffiths et al[27]). The values E_L greater than

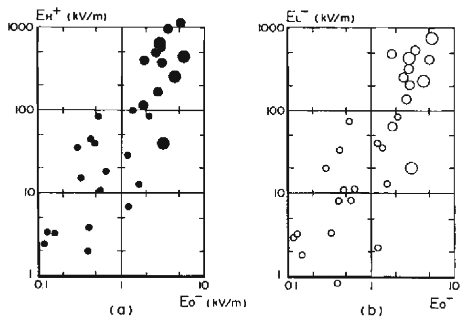

Fig. 10 Assessment of E_H (a) and E_L (b) derived from the theories of polarization charging and selective ion capture, respectively. The positive electric field E_H in the cloud and the negative one E_L beneath the cloud are estimated from raindrop charge-size relations of negative charges and positive ones, respectively. These are plotted against the maximum negative field E_0 on the ground surface. All the case studies during 1977–1981 are included, where the small circles, the medium ones and the large ones indicate continuous rain, non-thundery convective shower and thunderstorm, respectively.

this are quite unreasonable for those beneath the clouds. As described before, other charging processes are expected.

Besides the electric screening effect caused by the point discharge ions (Winn et al[28]), charges on falling raindrops may also play an important role on the surface electric field. The charge-size measurement enables us to elucidate possible vertical distribution of various electrical properties. Our preliminary estimation revealed that the effects of the raindrops as carriers of the space

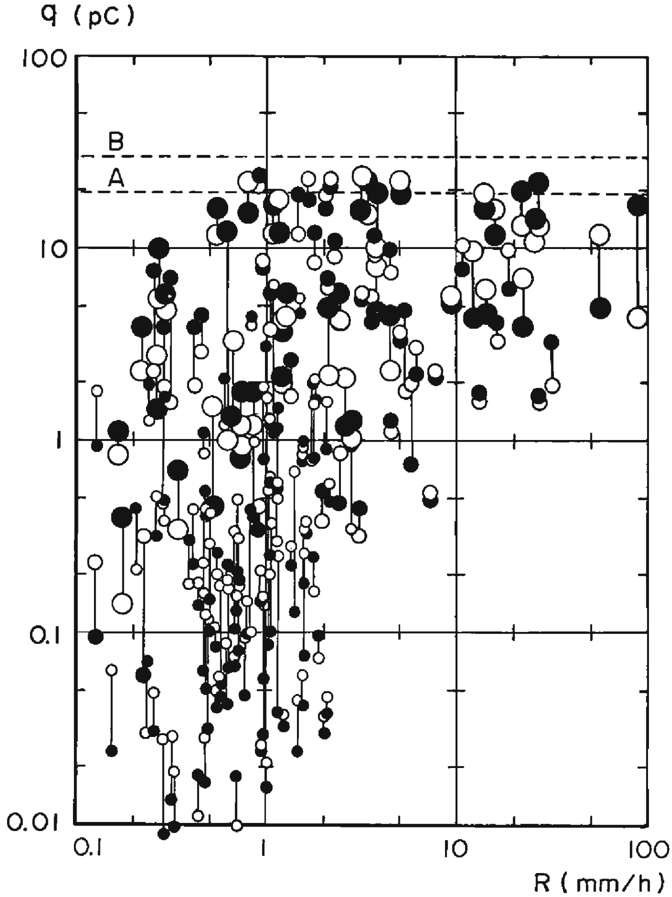

Fig. 11 The relation between the rainfall intensity R and the average charge q on a raindrop ($D=1.0\pm0.3$ mm), during every interval of 10 min., or in some cases, 5 min., when R exceeded 0.1 mm/h, for all the case studies durung 1977–1981. Open and closed circles represent the positive and negative charges, respectively. Large, medium and small circles indicate the thunderstorm, non-thundery convective shower and continuous rain, respectively. Broken lines A and B are the limitation of charging process under the breakdown field of lightning discharge (350 kV/m); A for polarization charging and B for selective ion capture.

charges are in some cases of rain overwhelming.

A recent review by Latham[29] pointed out that both the processes of selective ion capture and polarization charging are inadequate for explaining the thundercloud electrification and paid attention to the non-inductive charging through the interactions of different types of hydrometeors in thunderclouds. Fujiyoshi et al[14] implied an analogous charging processes in the stratiform clouds. Thus it is worth while correlating the charge of raindrops with the spatial distribution of hydrometeors that can approximately be substituted with the rainfall intensity.

The relation between the rainfall intensity R and the average charge q on a raindrop ($D=1.0\pm 0.3$ mm) is represented in **Fig. 11**. For all the case studies during 1977–1981, the values R and q are calculated for every period of 10 min., regardless of the polarity of the electric field. Such periods as the rainfall intensity is less than 0.1 mm/h are excluded. Even the non-thundery showers attain as intense charges as thunderstorms. Charging in a continuous rain is inferior. Some charges on convective rain slightly exceed the limit of polarization charging, while highly charged raindrops are exactly within the limitation of selective ion capture. It must again be noted, however, that the raindrops smaller than 1.0 mm in diameter easily experience high electrification beyond these limitations, as was implicable in **Fig. 10**.

Fig. 11 also implies the existence of the lower limit of raindrop charge that is nearly proportional to the rainfall intensity. It can be said that appreciable rainfall always causes a certain intensity of charging. This again supports the important role of interactions of hydrometeors on their charging, and perhaps, on the cloud electrification.

5. Conclusions

The instrument for the simultaneous measurement of charge and size of raindrops is described, and the results of the raindrop charge-size and surface electric field measurements for three typical rainfalls on the ground are also described.

The electric field disturbances accompanying the passage of precipitating convective clouds usually implied that those clouds were electrified in an ordinary polarity of dipoles. When the clouds was isolated and non-thundery, the field often carried out well defined W-shaped time change. Well known mirror-image relation between the polarity of raindrop charge and that of electric field seldom held; large raindrops which contributed most to the rainfall current as well as the rainfall mass flux, were charged negatively, the same in the polarity as the dominant surface electric field, though smaller ones carried appreciable positive charges to the ground.

The field disturbances associated with thunderclouds implied the existence of appreciable point discharge at the ground. Large raindrops showed the mirror-image relation, while smaller ones did not. In both cases of thundery and non-thundery, some of the raindrops carried excessive charges that couldn't be explained by the processes of inductive polarization charging or selective ion capture.

In the cases of continuous rain, weak electric field is not likely to affect selective ion capture. The positive charge on a raindrop and the negative one are nearly the same in magnitude and fluctuate almost in phase. The larger the raindrop diameter is, the earlier the fluctuation in the raindrop charge rises, which implies that the charging processes mainly exist aloft.

The relation of raindrop charge and the rainfall intensity showed the important role of interactions of hydrometeors on cloud electrification.

Acknowledgements

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